MADPH-95-886

University of Wisconsin - Madison

April 1995

Particle Production in Very High-Energy Cosmic-Ray Emulsion Chamber Events: Usual and Unusual Events

C. G. S. Costa and F. Halzen

Department of Physics, University of Wisconsin, Madison, WI 53706, USA

C. Salles

Department of Materials Science and Engineering,

University of Wisconsin, Madison, WI 53706, USA

(February 7, 2008)

Abstract

We show that a simple scaling model of very forward particle production, consistent with accelerator and air shower data, can describe all features of the very high-energy interactions recorded with emulsion chambers. This is somewhat surprising after numerous claims that the same data implied large scaling violations or new dynamics. Interestingly, we cannot describe some of the Centauro events, suggesting that these events are anomalous independently of their well-advertised unusual features such as the absence of neutral secondaries.

PACS number(s): 13.85

I. INTRODUCTION

In this paper we show that the simplest assumptions on particle production in the very forward direction, Feynman scaling and constant inelasticity, can provide a coherent description of air shower and emulsion data. All features of our model are approximately shared with QCD-inspired models [1] of high-energy particle interactions. The phase space populated by the secondaries in very-high-energy cosmic-ray interactions is, unfortunately, not covered by collider experiments which only view centrally produced particles. We therefore start the discussion with the simplest ansatz for the dynamics of particle production at large rapidities. In the end, this guess will turn out to be adequate in describing a wide variety of data.

In order to describe the underlying high-energy particle production dynamics common to accelerator, air shower and emulsion chamber data, we start with the simplest phenomenological model for the rapidity density distribution of charged pion production which we parametrize as

$$\frac{dN}{dy} = x\frac{dN}{dx} = a\frac{(1-x)^n}{x^m} \ , \tag{1}$$

where y is the rapidity of the produced secondaries. The Feynman variable x is given by the ratio of the secondary particle energy E to the incident energy E_0.

The $(1-x)$ power law in (1) describes the decrease in the number of particles produced with large x values, the $1/x$ term dictates the shape of the function at low x. Simple parton counting rules [2] imply that $n \simeq 3$ and $m = 0 - 1/2$. Eq. (1) reflects the approximate Feynman scaling behavior in the fragmentation region (large x, y) expected from QCD [1]. Our basic assumptions imply that the inelasticity K, i.e. the fraction of the collision energy going into the production of secondaries, is independent of energy. QCD-inspired models predict that $K = 0.6 - 0.65$ [3–5] at the energy region of interest. We have to account for nuclear target effects which can simply be done by allowing increased m-values to describe the enhanced production of low-x particles in nuclear collisions. Also, nuclear effects increase

the value of the proton-air inelasticity [6] to approximately 0.8. This simple picture is consistent with the little information one can extract from accelerator results on the production of particles in the very forward direction [7]. Especially in the high-energy collider experiments the phase space relevant to cosmic-ray data is usually obscured by the beam-pipe [8].

With this background we may investigate air shower and emulsion chamber results.

II. FORWARD PARTICLE PRODUCTION AND AIR SHOWERS

A QCD-based Monte Carlo simulation of ultra-high-energy cosmic-ray hadron interactions, which incorporates large p_t jet production, has been used by L.K. Ding et al. [9] (hereafter referred to as DKTY) to perform a detailed description of air shower observations. The rapidity distribution of secondary particles has been derived in this analysis [10], e.g. for interaction energies of 10^{16} eV ($\sqrt{s} \sim 4.3$ TeV) as illustrated in Fig. IV. Also shown in the figure is an adequate description of the resulting distribution using Eq. (1) with $a = 0.12$, $n = 2.6$ and $m = 1$, parameters quite consistent with our expectations. The analysis of reference [9] also shows that particle production in the forward direction exhibits approximate Feynman scaling, consistent with our simple assumptions.

The main point of this paper is that this model, in its simplest form, describes all the details of emulsion chamber experiments. This was somewhat surprising to us given the many claims of new dynamics and non-scaling behavior in the literature based on the same information; see *e.g.* Ref. [11]. Interestingly, we cannot describe some of the Centauro events. The rapidity distribution of the secondaries in these events pegs them as being anomalous, independently of their well-advertised unusual features such as the absence of neutral secondaries.

III. EMULSION CHAMBER DATA

Before proceeding with the study of emulsion chamber data, we first comment on a crucial aspect of the calculation: the mean inelasticity which is calculated through energy

conservation (using charged secondaries only)

$$\frac{2}{3}\langle K\rangle E_0 = \int_0^1 E_0\, x \left(\frac{dN}{dx}\right) dx \, . \tag{2}$$

The unphysical singularity of Eq. (1) on $x = 0$ is removed by the threshold effects in the measurement. The lowest energy particles in the cascade will not make it to observation level. We implement this by making the x-distribution constant below a certain value x_0, so that the mean inelasticity is

$$\langle K\rangle = \frac{2}{3}\, a \left[\int_{x_0}^1 \frac{(1-x)^n}{x^m} dx + \frac{(1+x_0)^n}{x_0^{m-1}}\right] . \tag{3}$$

The existence of a lower limit on x, resulting from inevitable energy-loss in the air cascade before it reaches the detector, is well known [12]. Emulsion chambers observe the debris of air showers initiated by cosmic rays one or more nucleonic mean-free-paths (mfp) above the detector. From the study of Ref. [12] one concludes that, because of the strong energy dissipation in the cascade, x_0 must be around 1×10^{-3} and 3×10^{-2} for mountain altitude measurements. We can obtain the same result from a back-of-the-envelope calculation. Take as an example the Ursa Maior event observed by the Brazil-Japan Collaboration [13]. Triangulation of the secondary charged tracks predicts that the first interaction occurred 2 or 3 km above the chamber, which represents approximately 2 mfp. At the first interaction the nucleon with energy E_0 releases on average around $\frac{1}{2}E_0$ to particle production and therefore $\frac{1}{6}E_0$ to each pionic component (π^0, $\pi^\pm$). After 2 more interactions, a charged pion would have on average $(E_0/6)^3$ so that $x_0 \sim (1/6)^3 \sim 5 \times 10^{-3}$. This value is consistent with the one obtained in Ref. [12] and, if used in Eq. (3), leads to $\langle K\rangle = 0.81$, matching the expected value; see Section I.

We will investigate experimental data obtained in large emulsion chambers, using rigorous analytical solutions of the diffusion equations for the hadronic cascade induced by one single nucleon in the atmosphere. The one-dimensional solution $F_H(E, E_0, t, t_0)$ enables us to calculate the integral energy spectrum of hadrons [14]

$$I_H(> E, E_0, t_f, t_0) = \int_E^{E_0} dE' F_H(E', E_0, t_f, t_0) \, , \tag{4}$$

which gives the number of hadrons with energy above E, at the detection level t_f for a cascade initiated by a nucleon with energy E_0 at atmospheric depth t_0. The three-dimensional solution $F_H(E, E_0, \mathbf{r}, t, t_0)$ is used to calculate the energy-weighted lateral spread [15,16]

$$N_H(> Er, E_0, t_f, t_0) = \int\int dE' d\mathbf{r}' \, H(E'r' - Er) \times F_H(E', E_0, \mathbf{r}', t_f, t_0) \,, \tag{5}$$

which evaluates the number of hadrons with energy times radial length greater than Er. The function $H(E'r' - Er)$ is the Heaviside function.

The only free parameters are the primary particle energy E_0 and the atmospheric depth t_0 of the first interaction. In our calculations we define the visible energy $E_0^{(\gamma)} = k_\gamma E_0$ (with $k_\gamma \sim \langle k_\gamma \rangle = 0.25$) and the atmospheric depths t in units of nucleonic mfp, with $\lambda_N = 80$ g/cm^2. We use for the transverse momentum $\langle p_t \rangle = 0.4$ GeV/c.

In Fig. IV we compare our results for the integral spectrum of the event Ursa Maior [13] detected at Mt. Chacaltaya (540 g/cm^2 or $t_f = 6.75$). We obtain $E_0^{(\gamma)} = 2930$ TeV, which corresponds in the center of mass system (c.m.s.) to $\sqrt{s} = 4.7$ TeV. The determined depth of the first interaction ($t_0 = 4.95$) is consistent with the expectation that the event started about 2 mfp above the chamber (see Table I). There is no data available on the energy-weighted lateral spread for this event.

In Fig. IV we show (a) the integral spectrum and (b) the energy-weighted lateral spread for the superfamily P3′-C5-505, detected by the Pamir Collaboration [17] at the detection level $t_f = 7.45$ (or 596 g/cm^2). In the same figure we present the results for the event Centauro VII, detected by the Brazil-Japan Collaboration [18]. For clarity, we have shifted in the figure the data of Centauro VII by a factor 10. The characteristics of both events are again summarized in Table I.

The investigation of Centauro I, also detected by the Brazil-Japan Collaboration [19,20], is presented in Fig. IV (see also Table I). We observe that neither the integral spectrum, Fig. IV(a), nor the energy-weighted lateral spread, Fig. IV(b), are reproduced by the analytical calculation. We verified that the origin of this discrepancy cannot be associated

with an increase of the transverse momentum of the secondaries, for which there is some experimental evidence.

IV. CONCLUSIONS

Guided by QCD-inspired models, we proposed a simple phenomenological model for the production of secondaries, based on approximate scaling in the fragmentation region. The model parametrization is consistent with the behaviour of air showers at ultra-high energies. We subsequently applied the model to the description of experimental data obtained in emulsion chambers at different mountain altitudes. Both integral spectrum and lateral spread of cosmic-ray superfamilies are successfully reproduced.

We noticed that Centauro VII is well described by the model. From our point of view, it is not really different from any other event resulting from normal strong interactions. Actually, it has been pointed out previously [15] that this event is not a "hard" Centauro, in the sense that it possesses a comparable number of hadrons and gamma-rays arriving at the top of the upper detection chamber. On the other hand, the investigation demonstrates that an event like Centauro I cannot be described with the same simple hypotheses, suggesting that this event is clearly anomalous, even before one considers their charge-to-neutral ratio.

ACKNOWLEDGMENTS

This research was supported in part by the Brazilian agency CNPq, in part by the U.S. Department of Energy under Contract No. DE-AC02-76ER00881, by the National Science Foundation under Contract No. DMR-9319421 and the University of Wisconsin Research Committee with funds granted by the Wisconsin Alumni Research Foundation.

REFERENCES

[1] For a review, see F. Halzen in *Proc. of the 21st International Cosmic Ray Conference*, Adelaide, Australia, ed. by R.J. Protheroe (Graphic Services, Northfield, South Australia, 1990), Vol. 12, p. 101.

[2] J. Gunion, Phys. Lett. **B88**, 150 (1979).

[3] T. K. Gaisser *et al.*, *Proc. of the 21st International Cosmic Ray Conference*, Adelaide, Australia, ed. by R.J. Protheroe (Graphic Services, Northfield, South Australia, 1990), Vol. 8, p. 55.

[4] B.Z. Kopeliovich *et al.*, Phys. Rev. **D39**, 769 (1989).

[5] L. Durand and H. Pi, in *Proc. of the 3rd Blois Conference on Elastic and Diffractive Scattering*, Nucl. Phys. B Proc. Suppl. **12**, 379 (1990).

[6] N.G. Jaoshvili *et al.*, Nucl. Phys. **B336**, 86 (1990).

[7] UA7 Collaboration,E.Pare *et al.*, Phys. Lett. **B242**, 531 (1990).

[8] See, however, J. D. Bjorken, *Fermilab Minimax Project*.

[9] L.K. Ding, K. Kasahara, S. Torii and T. Yuda, ICR report 107-83-1 (Tokyo, 1983); L.K. Ding, K. Kasahara, S. Torii and T. Yuda, *Proc. of the 18th International Cosmic Ray Conference*, Bangalore, India, ed. by N. Durgaprasad *et al.* (New Delhi, 1983), Vol. 5, p. 483.

[10] F. Halzen, *Proc. of the International Symposium on Cosmic Ray and Particle Physics*, Tokyo, Japan, ed. by A. Ohsawa and T. Yuda (Yamada, Tokyo, 1984), p. 777.

[11] A. Ohsawa and K. Sawayanagi, Phys. Rev. **D45**, 3128 (1992).

[12] A. Ohsawa and S. Yamashita, Prog. Theor. Phys. **77**, 1411 (1987).

[13] J.A. Chinellato, Ph.D Thesis, Universidade Estadual de Campinas, Brazil (1981).

[14] J. Bellandi *et al.*, Phys. Rev. **D50**, 6836 (1994).

[15] J. Bellandi, C. Salles and C.G.S. Costa, University of Wisconsin-Madison preprint MADPH-94-858 (1994).

[16] C. Salles, J. Bellandi and C.G.S. Costa, University of Wisconsin-Madison preprint MADPH-94-863 (1994).

[17] Pamir Collaboration and Chacaltaya Collaboration, A.S. Borisov *et al.*, *Proc. of the 20th International Cosmic Ray Conference*, Moscow, ed. by V.L. Kozyarivsky *et al.* (Moscow, 1987), Vol. 5, p. 383.

[18] Brazil-Japan Collaboration, J.A. Chinellato *et al.*, *Proc. of the 21st International Cosmic Ray Conference*, Adelaide, Australia, ed. by R.J. Protheroe (Graphic Services, Northfield, South Australia, 1990), Vol. 8, p. 259.

[19] C.G.M. Lattes, Y. Fujimoto and S. Hasegawa, Phys. Rep. **65**, 151 (1980).

[20] C.E. Navia *et al.*, Phys. Rev. **D50**, 5732 (1994).

TABLES

TABLE I. Determined parameters of emulsion chamber events analyzed.

Event	$E_0^{(\gamma)}$ (TeV)	t_0 (λ_N units)	$t_f - t_0$ (λ_N units)
Ursa Maior	2930	4.95	1.80
P3′-C5-505	3220	1.45	6.00
Centauro VII	7380	1.05	5.70
Centauro I	1890	5.75	1.00

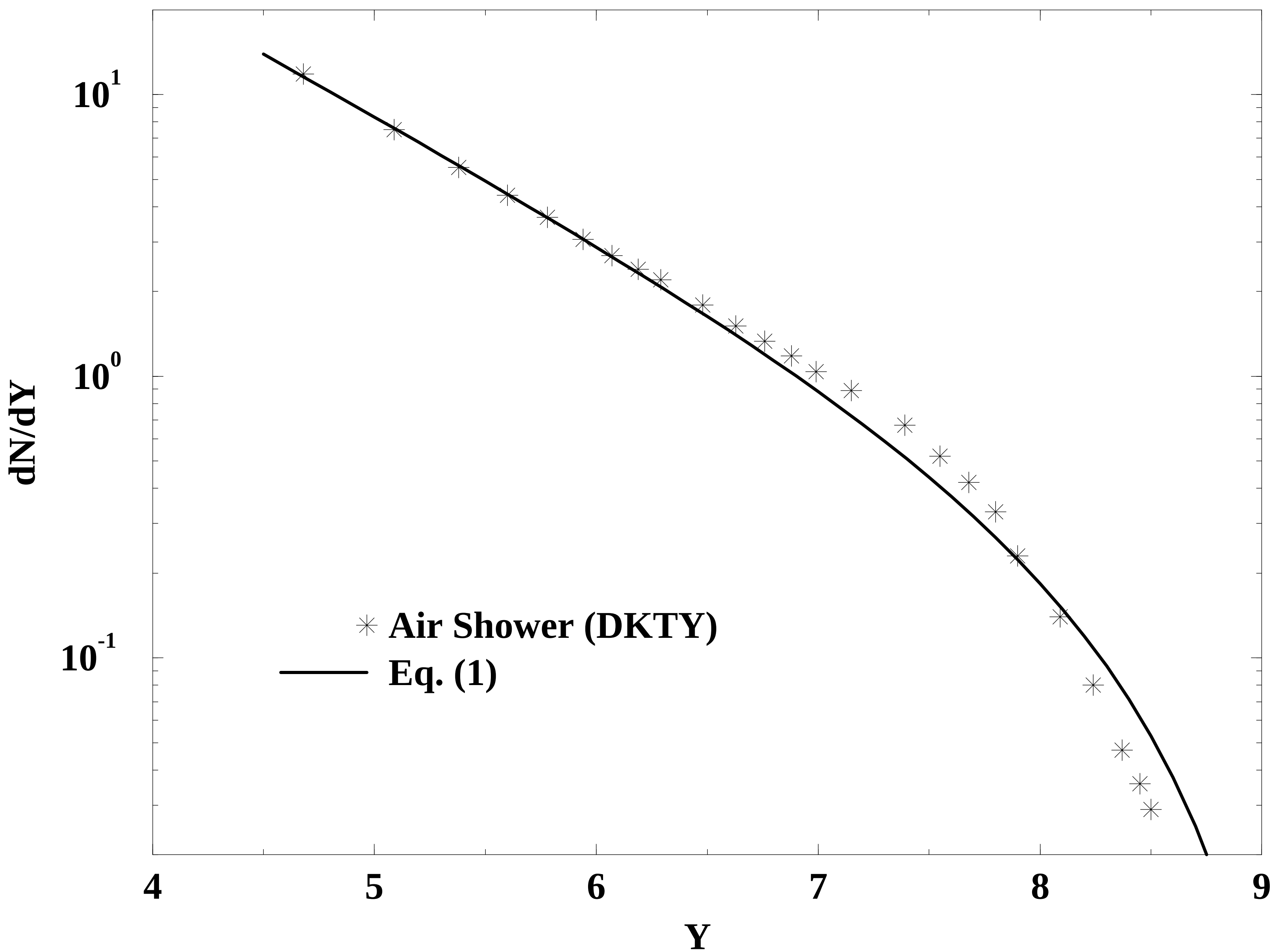
FIGURES

FIG. 1. Rapidity distribution of forward secondaries as derived from air showers with energy near 10^{16} eV, calculated by DKTY ($*$) and Eq. (1), with $a = 0.12$, $n = 2.6$ and $m = 1$ (solid line).

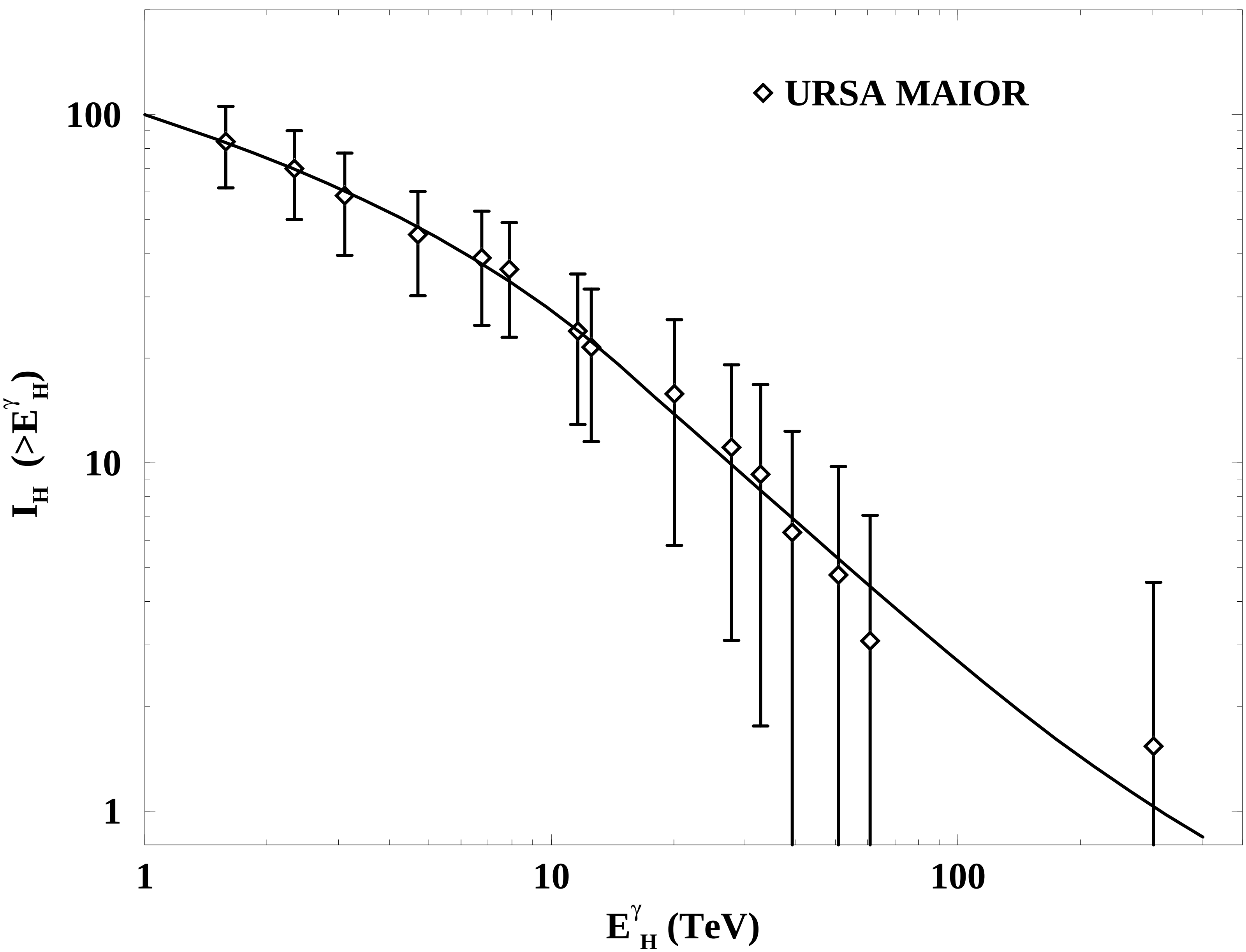
FIG. 2. Integral energy spectrum for the Ursa Maior event ($\diamondsuit$), detected at Mt. Chacaltaya [13], compared to the analytical calculation (solid line) using the x-distribution of Eq. (1). The fitted parameters $E_0^{(\gamma)}$ and t_0 are given in Table I.

FIG. 3. Description of the superfamily P3′-C5-505 ($\bigcirc$), detected by the Pamir Collaboration [17], and of the event Centauro VII ($\triangle$), detected by the Brazil-Japan Collaboration [18]. For illustrative purposes, the data of Centauro VII have been shifted by a factor 10. Solid lines are the analytical calculations for: (a) Integral energy spectrum, (b) energy-weighted lateral spread; parameters in Table I.

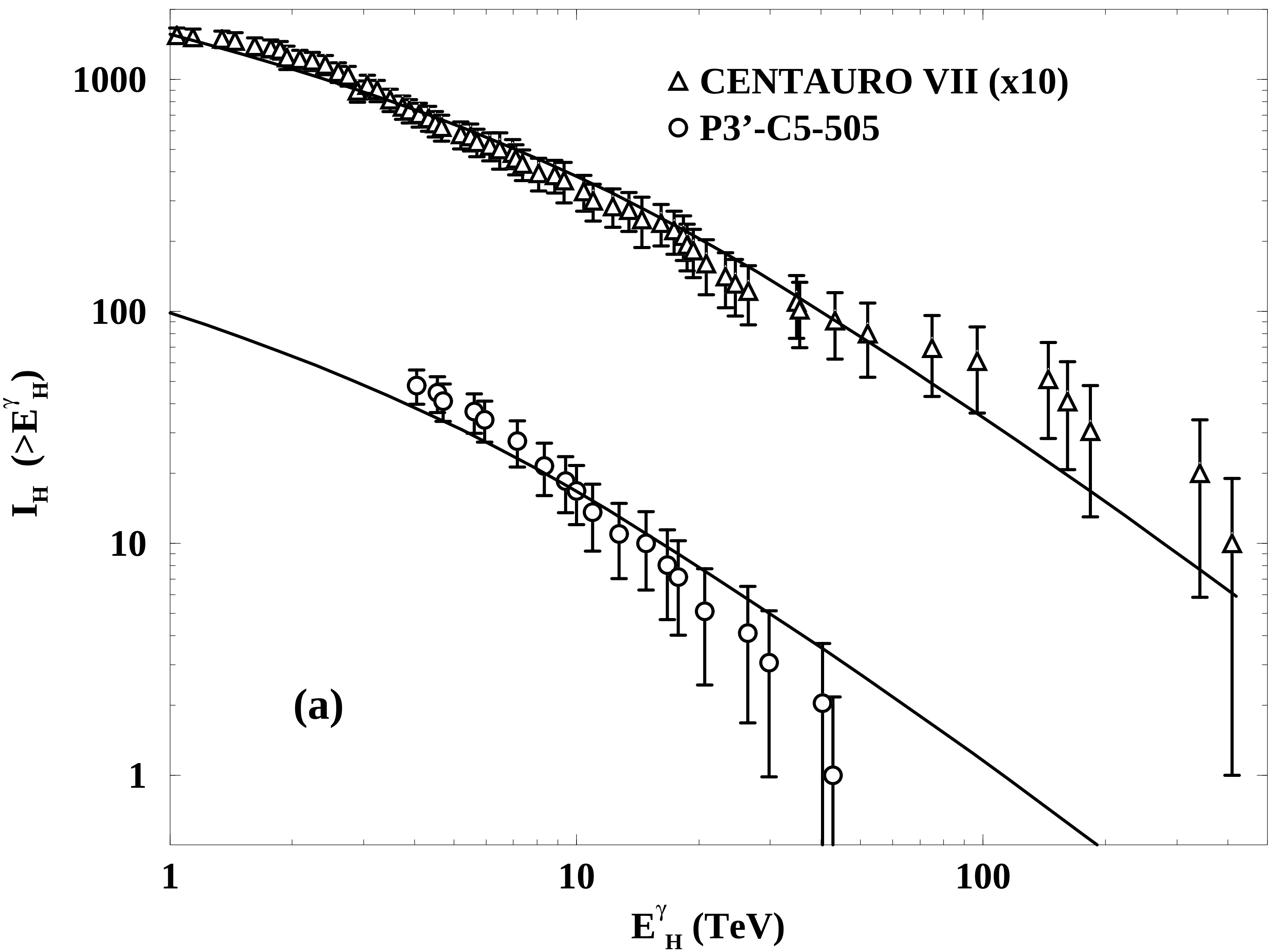
FIG. 4. Investigation of the event Centauro I ($\diamondsuit$), detected at Mt. Chacaltaya [19,20]: (a) Integral energy spectrum, (b) energy-weighted lateral spread. Solid lines are the analytical calculations; parameters in Table I.



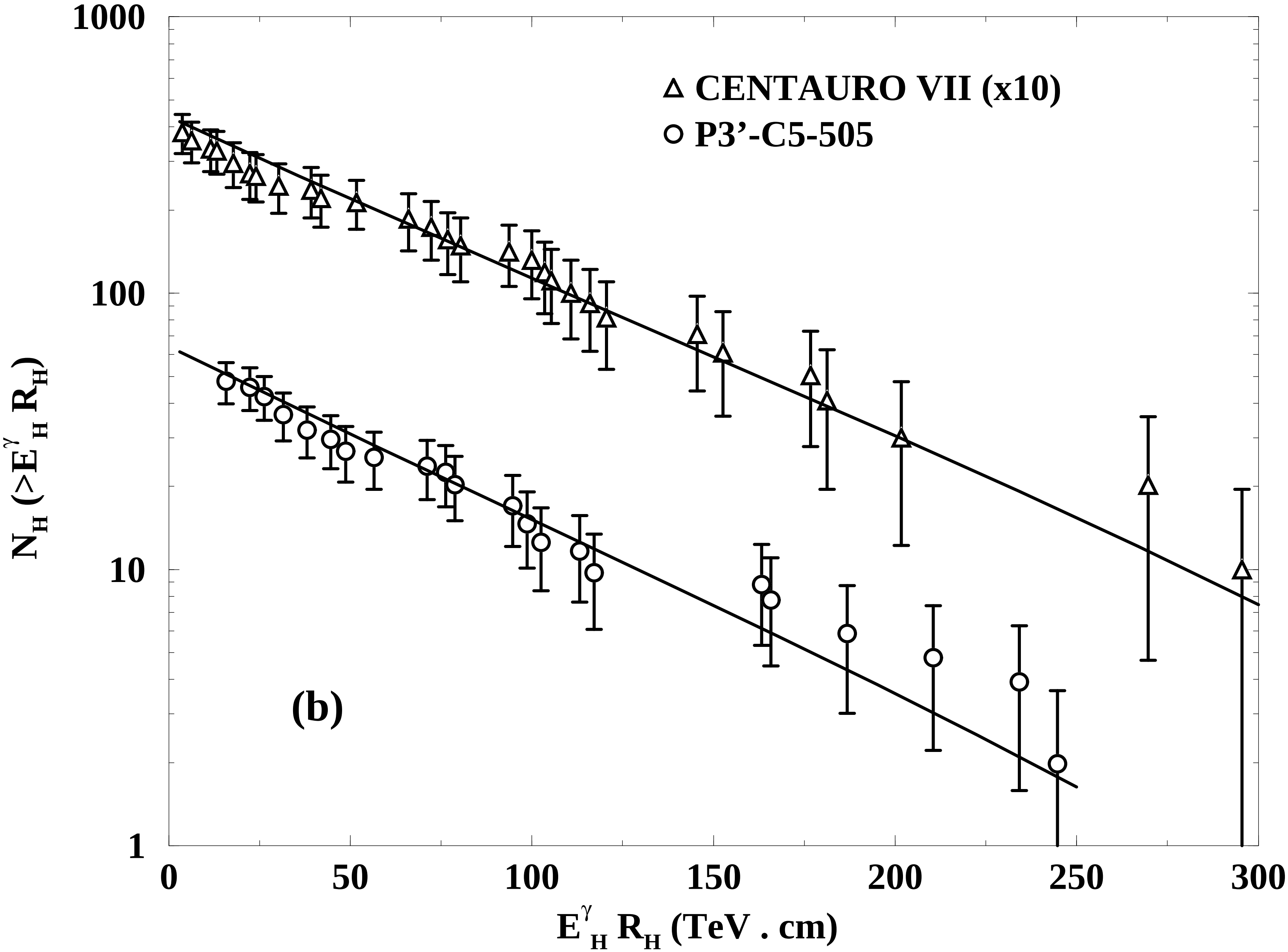
dN/dY
10^1
10^0
10^{-1}
4
5
6
7
8
9
Y
Air Shower (DKTY)
Eq. (1)



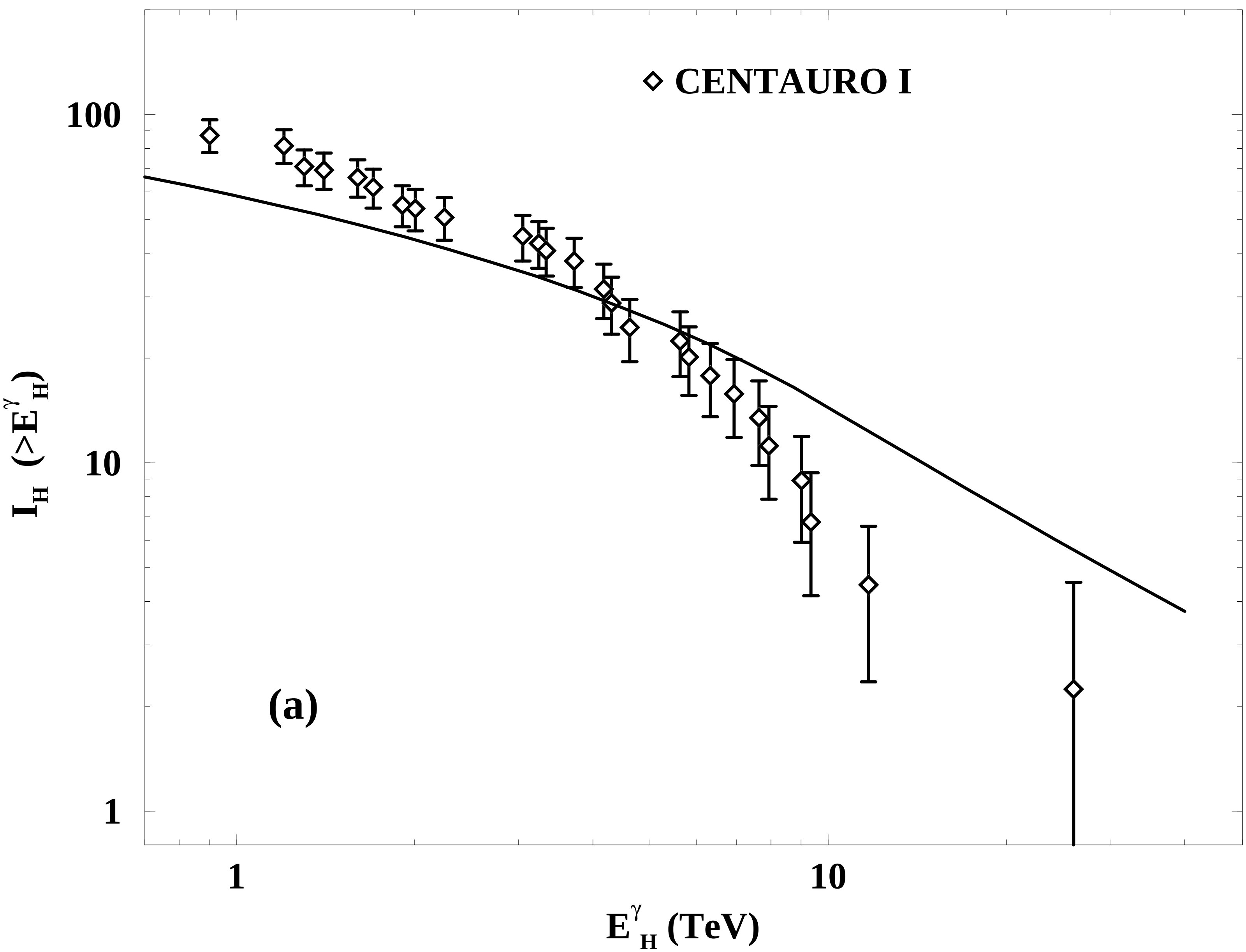
URSA MAIOR
100
10
1
1
10
100
$I_H\ (>E^{\gamma}_H)$
E^{γ}_H (TeV)

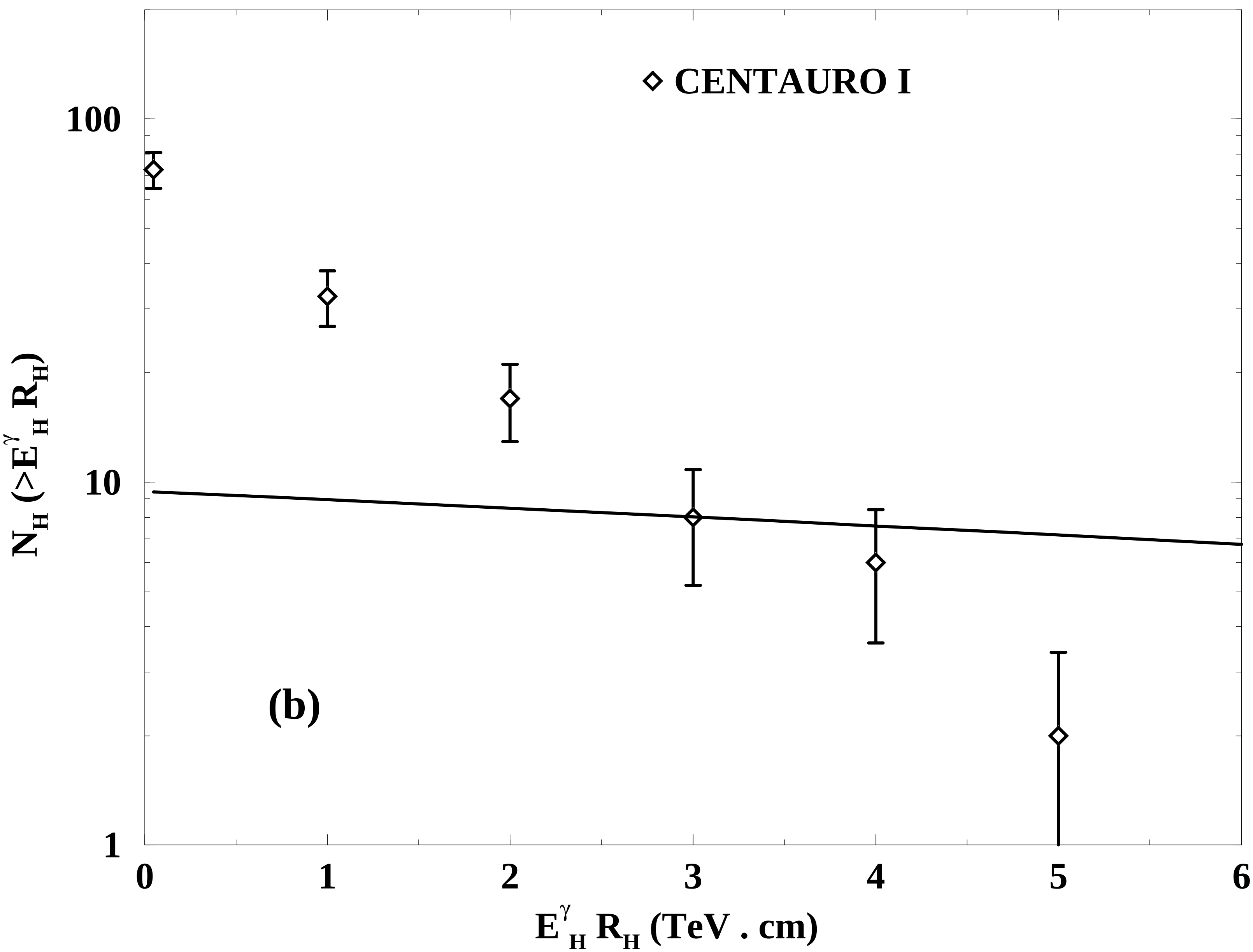


CENTAURO VII (x10)
P3'-C5-505
(a)
1000
100
10
1
1
10
100
I_H ($>E_H^\gamma$)
E_H^γ (TeV)



1000
100
10
1
0
50
100
150
200
250
300
CENTAURO VII (x10)
P3'-C5-505
(b)
$N_H\ (>E^{\gamma}_H\ R_H)$
$E^{\gamma}_H\ R_H$ (TeV . cm)


CENTAURO I
100
10
1
I_H (>E^γ_H)
(a)
1
10
E^γ_H (TeV)



CENTAURO I
100
10
1
(b)
0
1
2
3
4
5
6
N_H (>E'^{γ}_H R_H)
E'^{γ}_H R_H (TeV . cm)